DARK DOINGS

Searching for signs of a force that may be everywhere . . . or nowhere

BY RON COWEN

Ever since 1998, Robert Caldwell has been obsessed with something dark and repulsive. He spends nearly every waking moment trying to comprehend a mysterious entity that may be undermining gravity and pulling everything apart, making the universe expand at a faster and faster rate. This presumed force, sometimes called dark energy, might ultimately rip apart every object in the cosmos, from the tiniest of atoms to gargantuan clusters of galaxies (*SN: 2/28/04, p. 132*).

"It's both fascinating and terrifying," says Caldwell, a cosmologist at Dartmouth College in Hanover, N.H.

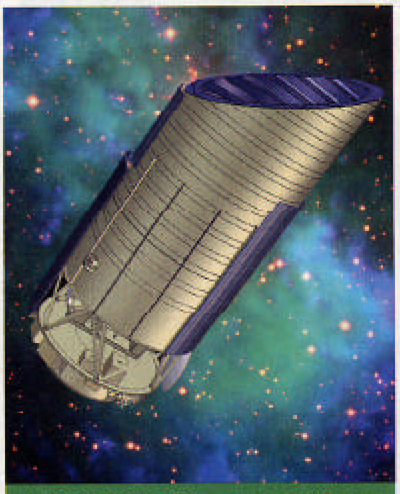
Caldwell has partners in his obsession, among them other theorists and the astronomers who dropped the bombshell about cosmic acceleration onto the scientific community 6 years ago. That's when two studies of distant exploding stars first revealed that the universe is accelerating its rate of expansion—exactly the opposite of what had been expected. The mutual gravity of all the matter in the cosmos ought to be slowing down the expansion that began with the Big Bang. The new observations led the teams to propose that there was something previously unimagined pushing everything away from everything else.

"It's kind of amazing that it's only been 6 years" since those findings, says observer John Tonry of the University of Hawaii in Honolulu, "because it now seems so much a part of the canonical lore that we believe about the universe."

Now, several teams of researchers are conducting experiments and planning ambitious new ones to investigate this suspected force. On the cosmic scale, astronomers are developing new sky surveys in search of supernovas while also studying the shapes of galaxies and the evolution of galaxy clusters. On a small scale, particle physicists are turning to atom-smashing experiments that may reveal whether the mystery lies in hidden spatial dimensions or in as-yet-undiscovered fundamental particles.

"When you have a big problem, you throw everything you can at it," says Joseph Lykken of Fermi National Accelerator Laboratory in Batavia, Ill.

Cosmic acceleration is "not just another mystery," says Lykken. "It's getting at something fundamental in our understanding of gravity, energy, and quantum theory. It may take us 20 years to [figure it out], but it will open a whole new chapter in physics, a revolution in our understanding of the world."



SUPER TELESCOPE — A proposed design for the Supernova Acceleration Probe.

R. LAFEVER, LBNL

SEEKING SUPERNOVAS In trying to identify the origin of this cosmic push, researchers are simultaneously considering two divergent and equally bizarre scenarios. In one approach, researchers embrace the concept of dark energy and look for the fingerprints of this unseen entity, which may spread uniformly through the cosmos and be an intrinsic property of empty space.

The other strategy denies dark energy's existence and instead seeks to explain cosmic acceleration by modifying the laws of gravity. According to this perspective, the wildly successful theory of gravity developed by Albert Einstein needs revision, especially as it describes gravity over large distances.

If dark energy is real, a special type of supernova may shine a light on its properties. Known as type 1a supernovas, these stellar explosions all have about the same intrinsic brightness, like light bulbs of similar wattage. A comparison of that fixed brightness to the brightness with which each supernova appears on the sky enables astronomers to measure the distance to each of these stellar explosions. By recording the spectrum of light emitted by a type 1a supernova, astronomers learn how fast its host galaxy was receding at the time the supernova erupted. With the information on the distance and recession velocities from many supernovas, astronomers can reconstruct how fast the universe was expanding at different times during its history.

From the 200 or so type 1a supernovas that astronomers have now studied, they've deduced that galaxies today are flying apart faster than they did 5 billion years ago—prima facie evidence for runaway expansion. Now, researchers want to learn whether the presumed dark energy has had the same density throughout cosmic history.

If its density is constant, then dark energy may resemble what Einstein called the cosmological constant—an unchanging property of empty space that imbues the universe with a constant acceleration. If dark energy's density varies, it could either increase in strength and rip the universe apart, or it could fade away. In the latter case, the gravitational tug of all the matter in the universe would eventually cause the cosmos to collapse.

By the end of the decade, astronomers hope to have a telescope that will find thousands of type 1a supernovas and produce enough data to reveal whether or not dark energy has varied. For example, the Supernova Acceleration Probe, an orbiting satellite bearing a 1.8-meter telescope and the largest solid-state camera ever constructed, would image and take spectra of some 6,000 supernovas. If it gets funded by NASA and the Department of Energy, the 3-year mission could be launched by 2010. However, the project's funding has been delayed by NASA's recent presidential mandate to focus on human exploration of the moon and Mars.

CLUSTER CONNECTION In addition to studying explosions inside individual galaxies, astronomers are also trying to glimpse dark energy's effects by determining when and how clusters of galaxies coalesced.

The evolution of clusters-or any massive cosmic structure whose formation depends on gravitational attraction-is closely tied to the strength of dark energy. Early in the universe, when the density of matter was high, gravitational attraction would have handily won the tug-of-war with dark energy's repulsive force. Later, as the universe expanded more and more, matter became more dilute, permitting dark energy's push to overpower it. So, in a universe brimming with dark energy, clusters must form early or they won't form at all.

The earlier the galaxy clusters formed, the stronger dark energy must be. To determine how far back in time most clusters coalesced, astronomers must find the most distant ones. One technique is to look for signs of the hot, X-ray–emitting gas that bathes clusters. The proposed Dark Universe Observatory, a suite of seven Earth-orbiting telescopes, would scan a large chunk of the sky in search of the X rays. Astronomers will then combine the X-ray data with information already in hand from the Sloan Digital Sky Survey, which has recorded the distances to several hundred thousand galaxies. The results are expected to indicate when galaxy clusters formed.

Other cluster watchers examine the cosmic microwave background, the radiation left over from the Big Bang. When photons from that background strike the hot gas surrounding a cluster, they gain energy. It's this shift in photon energy, known as the Sunyaev-Zeldovich effect, that John E. Carlstrom of the University of Chicago and his colleagues will be examining in unprecedented detail beginning late this summer.

Using their new Sunyaev-Zeldovich Array of six 3.5-m radio receivers at the Owens Valley Radio Observatory near Big Pine, Calif., Carlstrom and his collaborators expect to find thousands of new clusters. Several other teams are building similar radio telescopes. And in 2007, Carlstrom expects to have finished building an even more sensitive detector of clusters, a radio telescope at the South Pole.

Another search strategy for signs of dark energy takes advantage of a cosmic distortion known as gravitational lensing. Because any massive object causes space-time to curve, it can bend the path of a light ray emitted by a body, such as a galaxy, that lies behind it. The shape of that body appears distorted, as if the light had passed through a thick glass lens. In so-called weak lensing, light emitted by the outer parts of distant galaxies is distorted by the gravity of all the individual galaxies that lie in front of it.

Weak lensing relates to dark energy because the expansion rate of the universe determines how much volume lies between distant galaxies and Earth. Dark energy's push would increase the volume of space, making it more likely that light traveling to Earth from a distant galaxy would pass near other bodies and exhibit weak lensing. Dark energy would also require clumps of matter to begin coalescing into galaxies earlier in the history of the universe, also increasing the chances for lensing to occur.

To perceive the small effect of weak lensing, astronomers will have to study millions of galaxies distributed across the sky. The proposed Large Synoptic Survey Telescope, an 8-m ground-based instrument, could open for business in 2011. The orbiting Supernova Acceleration Probe could also lend a hand in weak-lensing studies.

GETTING PARTICULAR Dark energy may also reveal itself on the subatomic scale. Particle physicists at Fermilab and other high-energy physics laboratories are paying close attention to the neutrino, an elementary particle known to come in three flavors-tau, muon, and electron. A decade ago, scientists discovered that each type of neutrino could transform into the others. These so-called oscillations indicate that neutrinos, which for decades were thought to be massless, actually have some weight.

Dark Musings

A springboard to space?

The notion that gravity can be repulsive instead of attractive may sound bizarre, but it has its roots in Einstein's general theory of relativity. The theory states that mass isn't the only source of gravity. Pressure also exerts a gravitational force. There's a further complication because pressure can be positive or negative. And if pressure happens to be negative, gravity pushes rather than pulls.

Positive pressure is the familiar type, like that exerted by an inflated balloon. You have to expend energy in order to compress it. Something with negative pressure acts like a spring—you have to expend energy to stretch it. That's why theorists say that dark energy imbues space with a springiness, notes David H. Weinberg of Ohio State University in Columbus.

Taking the spring analogy further, he says that the question of whether the density of dark energy varies over time is equivalent to asking how hard it is to compress the springiness of space. If the density of dark energy is constant, as in the cosmological-constant model, then dark energy is difficult to compress, as if you're dealing with an especially stiff spring. Models in which dark energy varies with time are akin to imbuing space with a more flexible spring. Observers are now trying to determine the compressibility. —R.C.

Theorists have homed in on what may be a deep connection between dark energy and particle physics. Mass and energy are equivalent, according to Einstein, and scientists have noticed that the energy scale associated with dark energy, about one-thousandth of an electronvolt, is approximately the same as the masses associated with the three known types of neutrinos. Assuming that this isn't a coincidence, scientists have been trying to identify a single quantum mechanical description that applies to both dark energy and neutrinos.

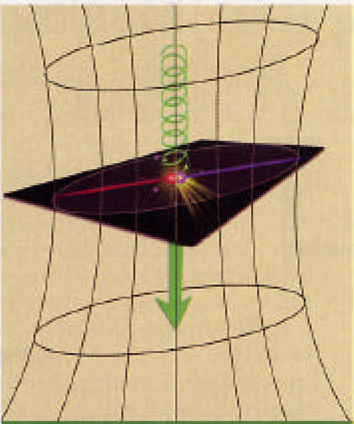
They've found that neutrino oscillations can be described by a time-varying field that resembles the time-varying dark energy described in some models. However, these models also predict a fourth type of neutrino for which there is yet no experimental evidence.

In a series of ongoing experiments at Fermilab, scientists are searching for that missing neutrino. In these studies, a beam of muon neutrinos crosses a 30-foot tank of mineral oil. Some 520 light detectors lining the tank record the flashes that occur when neutrinos strike carbon nuclei in the tank. An analysis of those flashes has yet to reveal evidence of a fourth neutrino, but the experiment is set to continue for another 2 years.

GRAVITY ON THE FLY Despite the interest in time-varying dark energy, an unchanging energy density akin to the cosmological constant now appears to be the more accurate model for the brand of dark energy that might exist in our universe, says cosmologist Sean Carroll of the University of Chicago. Yet for Carroll and other theorists, the notion of a cosmological constant is downright distasteful.

For starters, the only source that scientists have come up with for an unvarying dark-energy density is the energy associated with the vacuum of space. As described by quantum theory, the vacuum seethes with the relentless creation and annihilation of subatomic particles and their antiparticles. But calculations show that the density of this vacuum energy is a whopping 10^{120} times as big as that of dark energy. Such a glaring discrepancy makes it hard for Carroll and others to fully embrace the cosmological-constant model.

Then there's the cosmic-coincidence scandal. The density of matter in the universe has steadily declined since the Big Bang, and measurements show that today it's about the same as the density of dark energy predicted by the cosmological-constant models. There's only a 1 percent chance, Carroll calculates, that observers would be living at a time when the density of dark energy and matter were comparable. For some physicists, this match is too unlikely to be true.



OUTER LIMITS — Illustration of how gravity might leak out of our four-dimensional world into hidden dimensions, thus explaining why the cosmos is revving up its expansion.

Instead of accepting dark energy, these scientists would rather try to account for the acceleration of the universe's expansion by tinkering with Einstein's general theory of relativity.

Gia Dvali of New York University and his colleagues propose that gravity parts company with Einstein's theory because some of it leaks away into extra, hidden dimensions. They suggest that the universe as we know it—galaxies, stars, and familiar elementary particles—is confined to a four-dimensional space-time, called a brane, that's embedded in a higher-dimensional world.

Because gravity is an intrinsic property of all of space-time, however, it may be the only component of the cosmos that isn't trapped on this four-dimensional brane, Dvali suggests. He compares the scenario to what happens when a metal plate submerged in water is struck with a hammer. As the plate—representing the brane—vibrates, some of the sound waves escape into the surrounding water—representing higher dimensions.

When gravitons, the particles that mediate gravitation attraction, escape the local brane, the gravitational force that remains within the brane diminishes. The weakening of gravity shows up as an increase in the rate of cosmic expansion. In this way, leaky gravity looks and behaves much like dark energy.

Dvali and his collaborators are still fleshing out their model, but it already has some concrete predictions measurable within our own solar system. Leaky gravity, it turns out, should cause the moon to tilt ever so slightly in its orbit about Earth. New measurements are looking for such a precession by using ground-based lasers that bounce off mirrors that the Apollo 11 astronauts left on the moon 3 decades ago.

Hidden dimensions and leaky gravity may also reveal themselves in experiments at Fermilab (*SN: 2/19/00, p. 122*). At extremely high energies, collisions between two particles, such as a proton and an antiproton, should produce a graviton, along with a spray of other particles. Those other particles will remain trapped on a four-dimensional brane, but the graviton can escape. If it does so, then there ought to be a noticeable deficit in the amount of energy recorded. Such missing energy would serve as a signpost of the universe's higher dimensions and a gravitational theory that goes beyond that of Einstein.

No such missing energy has yet been detected, but physicists continue to search. "We had the capability to look for this before, but people didn't' think [the notion of higher dimensions] was a reasonable idea. Now, people have started to take this seriously," says Lykken.

Whether it's dark energy that rules the universe or a kind of gravity that goes beyond what Einstein had imagined remains to be seen. Whatever the answer is, Caldwell notes, it's bound "to answer some deep questions about the universe." ■

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